Cluster observations of currents in the plasma sheet during reconnection

I. V. Alexeev,[1] C. J. Owen,[1] A. N. Fazakerley,[1] A. Runov,[2] J. P. Dewhurst,[1] A. Balogh,[3] H. Rème,[4] B. Klecker,[5] and L. Kistler[6]

Received 5 September 2004; revised 9 November 2004; accepted 17 November 2004; published 2 February 2005.

[1] We present Cluster PEACE observations of parallel electron currents near a reversal of accelerated ion flows which indicated that the spacecraft were in the vicinity of an active reconnection X-line (XL). Moments calculated from the PEACE electron spectrometer 3D 4s resolution data are analysed. We surveyed the electron current structure to reveal their dependence on distance from the neutral sheet (NS). The electron density and the magnetic field component parallel to the lobe magnetic field were selected as proxies of the distance to the NS. We found that earthward from the XL the electron parallel current switches direction: tailward closer to the NS and earthward nearer to the lobe. On the interface between the tailward and earthward currents we found a narrow layer of strong earthward current. At the same place the largest transverse magnetic disturbances were detected. The observed current structure is consistent with the collisionless reconnection model. However, tailward of the XL no such structure was evident in the data.
Citation: Alexeev, I. V., C. J. Owen, A. N. Fazakerley, A. Runov, J. P. Dewhurst, A. Balogh, H. Réme, B. Klecker, and L. Kistler (2005), Cluster observations of currents in the plasma sheet during reconnection, *Geophys. Res. Lett.*, *32*, L03101, doi:10.1029/2004GL021420.

1. Introduction

[2] Magnetic reconnection is believed to be a crucial process controlling plasma dynamics in the magnetosphere. Its occurrence in the magnetotail was predicted theoretically and verified by observations [e.g., *Sonnerup*, 1979; *Semenov et al.*, 1998; *Nagai et al.*, 2001].

[3] The particular mechanism responsible for the breakdown of the frozen-in condition in the diffusion region is not yet clear. Direct, in-situ experimental clarification of this issue is difficult due to the expected small size of the diffusion region and, hence, the low probability of in-situ spacecraft observations. Currently collisionless or Hall reconnection models are very promising as an explanation of this phenomenon. These models are appropriate when density and magnetic field gradient scales are comparable with the ion inertia length, c/ω_{pi}, and the Hall term in the magnetic induction equation becomes significant, so ions cease to move with the magnetic flux tubes [*Sonnerup*, 1979]. The occurrence of such thin current sheets in the magnetotail has been reported [*Runov et al.*, 2003]. This confirms that collisionless reconnection mechanisms are important in magnetotail dynamics.

[4] If a localised plasma sheet (PS) region becomes sufficiently thin, the reconnection diffusion region may form and a magnetic XL will appear. In the ion diffusion region, ions decouple from the magnetic field while the electrons continue to convect with magnetic flux tubes towards the XL until a smaller spatial scale, the electron inertia length, is reached. The resulting Hall electric currents in the diffusion region must close somewhere outside the diffusion region through a system of field-aligned electron currents. We will refer to these currents as the "Hall current system", bearing in mind that only the transverse currents in the diffusion region are actually caused by the Hall effect [e.g., *Nagai et al.*, 2003, Figure 9]. The Hall current system was predicted theoretically [*Sonnerup*, 1979] and is clearly identified in numerical experiments [*Lottermoser and Scholer*, 1997; *Birn et al.*, 2001; *Shay et al.*, 2001]. In the magnetotail the outflowing current layer arises in the plasma sheet boundary layer (PSBL) and inflowing current layer is inside the PS [*Fujimoto et al.*, 2001]. Several observations have been interpreted as a magnetotail Hall current system occurrence [e.g., *Nagai et al.*, 2001; *Runov et al.*, 2003]. Mostly these studies concerned observations of quadrupole magnetic field disturbances, produced between the inflow and outflow branches of the Hall current system and directed parallel the XL. The major problem of this approach is the necessity to accurately determine the reconnection layer orientation. Otherwise false magnetic signatures could arise from a relatively strong background magnetic field, even for small errors in the determined current sheet normal direction.

[5] From this point of view, direct studies of field-aligned electron flows in the PS and PSBL during reconnection are desirable as a direct and reliable way to confirm the role of the Hall effect in this process. In several GEOTAIL reconnection studies, electron moments were presented, but these were calculated for preselected electron distributions, and no more than a couple of dozen for an event [*Nagai et al.*, 2003].

[6] In this paper we present the results from the Cluster electron spectrometer PEACE [*Johnstone et al.*, 1997], using 3D electron distributions which are available each spacecraft spin during burst mode. We determine the structure of electron currents across the PS and PSBL for

[1]Mullard Space Science Laboratory, University College London, Surrey, UK.
[2]Institut für Weltraumenforshung der ÖAW, Graz, Austria.
[3]Imperial College, London, UK.
[4]CESR/CNRS, Toulouse, France.
[5]Max-Planck-Institut für extraterrestrische Physik, Garshing, Germany.
[6]University of New Hampshire, Durham, New Hampshire, USA.

0094-8276/05/2004GL021420$05.00

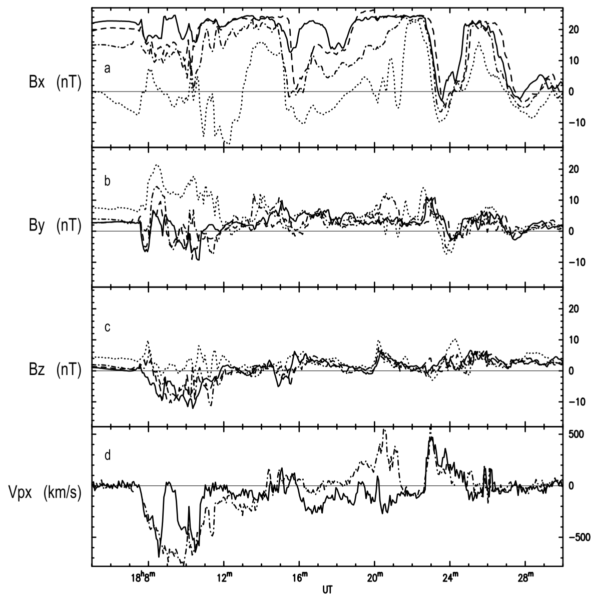

Figure 1. Cluster magnetic field and ion flow measurements: (a–c) GSM Components of the FGM magnetic field, (d) X component of the proton bulk velocity (CIS). Data from SC1 is shown as a solid trace, SC2 as a dashed trace, SC3 as a dotted trace and SC4 as a dash-dotted trace.

the substorm reconnection event of September 13, 2002. A sequence of 360 data points is used to survey the region earthward of the XL, which is several times more in number than in all previous studies. The averaged electron current density distribution cross-sections obtained during this event are compared with the expectations of the Hall reconnection model.

2. Observations and Data Analysis

[7] At 18:07 UT on September 13, 2002 the Cluster constellation was located at GSE coordinates (−17.5, 1.5, 2.9) R_e. At this time the spacecraft (SC) form a nearly regular tetrahedron with separations ~3000 km. SC 1, 2, 4 were located in the northern PSBL, while SC 3, which was situated ~2000 km in the negative z GSE direction relatively to the others, was inside the PS. Figures 1a–1c show the 3 components of the magnetic field, measured by the FGM instrument [*Balogh et al.*, 2001] while Figure 1d shows the x-component of the ion flow velocity from the SC 1 and 4 CIS/CODIF instruments [*Rème et al.*, 2001] for the period 18:05–18:30 UT. At ~18:07 UT both available CIS instruments detected an accelerated tailward proton flow, which lasted for ~5 minutes and during which the magnetic field had a persistent negative *z* component at SC 1,2,4.

[8] At ~18:13 UT SC 1,2,4 moved into the tail lobe, and up to 18:19 UT CIS observed no significant proton bulk flows. Around 18:15 UT SC 2 and 4 abruptly returned to the central plasma sheet. Later CIS on SC1 and SC4 observed fast earthward flows inside the PS (SC1 from 18:19–18:21 UT and both SC1 and SC4 from 18:23–18:25 UT).

[9] These features are consistent with reconnection taking place at the NS during this period. Fast plasma flows are identified as accelerated reconnection outflows. Moreover, since a flow reversal was observed, the reconnection XL passed close to the Cluster constellation as it moved tailward. This event is thus appropriate for studying processes in and around the diffusion region. It is apparent from the observations that conditions were turbulent and unsteady, particularly for the tailward flow interval, so the multi-spacecraft analysis techniques are difficult to apply in this case. However, the ability of Cluster to observe different regions of PS at the same time, and the effective increase of resolution are important in this case.

[10] We concentrate now on a statistical study of the moments of the electron 3D phase space distributions obtained by PEACE electron spectrometer for this event. These distributions are available each spacecraft spin (every 4s), since the data flow was in burst mode. Electron densities and velocities were calculated on the ground by integration over PEACE energy range from the spacecraft potential level to the upper limit of 26 keV. The statistics are analysed separately for earthward and tailward proton flow intervals. As the spacecraft moved across the PS and sampled different parts at different times, it is advantageous to rearrange the observations as a function of position of each spacecraft inside the PS. We examine the parallel electron flow structure in the PS and PSBL as ordered by the component of magnetic field lying parallel to the external lobe field, i.e., $B^* = \mathbf{B} \cdot \mathbf{n}_{lobes}$, where $\mathbf{n}_{lobes}$ is the magnetic field unit vector in the north lobe, and by the electron density N_e. These parameters are used as proxies of the spacecraft distance from the NS. Average parallel electron currents $eN_eV_{e\|}$ were determined as a function of B^* and N_e. The picture of electron flow distributions across the PS in the earthward ion flow interval is shown in Figures 2a and 2b. Since observations were made north of the NS, positive parallel currents flow earthwards and negative currents tailward. The axes are restricted to the interval [−40; 40] nA/m^2, so a few strong current bursts (up to 70 nA/m^2, see later) are outside the ranges of these panels. The averaged electron parallel current changes sign somewhere in the PSBL ($B^* \approx 15–18$ nT, $N_e \approx 0.18–0.20$ cm^{-3}), so for this interval average electron flow is tailward for the outer part of the PSBL and earthward for the inner PSBL. Data points in these figures are widely scattered, due to the turbulent conditions near the diffusion region and the dynamic nature of the electron population. For steady conditions, the averaging provides a measure of the net current density across the PS, which allows comparison to the magnetic field disturbances. This is shown in the Figure 2c, where the *y* component of the magnetic field transverse to the lobe magnetic field i.e., $\mathbf{B}_{\perp y} = \mathbf{B} - B^*\mathbf{n}_{\rm lobes}$ is plotted versus B^*. Note a pronounced maxima in the $B_{\perp y}$ distribution at $B^* \approx 15–22$ nT (and correspondingly at $N_e \approx 0.15–0.20$ cm^{-3}, not shown). This magnetic field disturbance is consistent with the existence of the Hall current system, and validates the electron current observations.

[11] In Figure 3 electron currents are presented as a time series together with the electron density and magnetic field data for the interval 18:18–18:24 UT, when the XL was tailward of the spacecraft. Note that as they move out of the PS, each spacecraft observe a strong (40–70 nA/m^2) electron current burst, as indicated by vertical lines. These

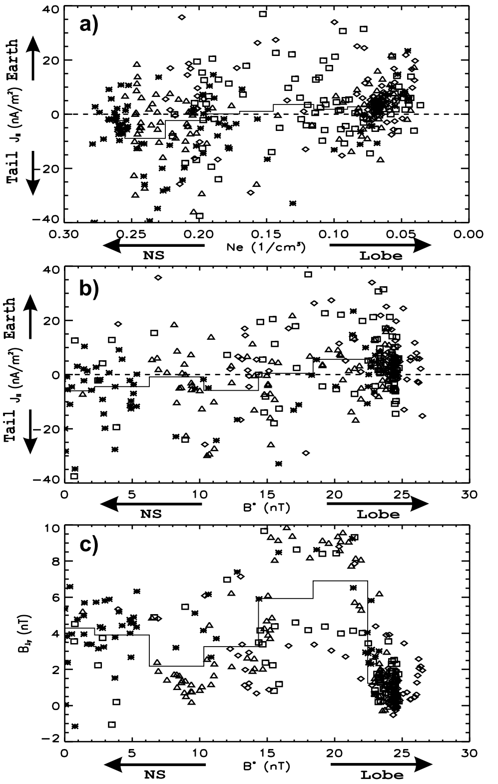

Figure 2. Electron parallel current (a,b) and correspondent magnetic field disturbance $B_{\perp y}$ (c) as a function of (a) N_e and (b,c) $B^* = \mathbf{B} \cdot \mathbf{n}_{lobes}$. Data points shown are for the time interval (18:18 UT–18:25 UT) when the X-line was tailward of Cluster. The solid histogram indicates the averaged values in each bin. Bin sizes are 0.03 cm^{-3} for (a) and 4 nT for (c). For convenience vertical axes at (a) and (b) are restricted to the interval [−40, +40] nA/m^2. The □, ◇, * and △ symbols denote spacecraft 1,2,3 and 4, respectively.

bursts occur at $B_x \approx 18$ nT, $N_e \approx 0.15$ cm^{-3}, in each spacecraft approximately in the same place the sign change of the averaged parallel electron current takes place. They are approximately coincident with the highest density gradients. The observed strong parallel current layer is very narrow and detected only in a few data points, so it hardly affects the statistical averages.

[12] During this period, the plasma was in a very turbulent state due to the adjacent active XL. The electron distributions were highly variable but it is still possible to recognise different distributions in the PS. In the CPS these are quite isotropic, even when the electron velocity is substantial. The electron current here is directed tailward. In the PSBL the distributions are highly variable, but mostly show bi-directional field-aligned beams with maximum differential energy flux at energies 1–2 keV. Unbalanced bidirectional beams in this region form a wide earthward field-aligned current layer from $B^* \approx 15$ nT ($N_e \approx 0.15$) to the lobe. On the NS side of this layer we observed unidirectional distributions which formed a narrow layer of strong earthward field-aligned electron currents. The maximum differential energy flux also occurred at energies of 1–2 keV.

[13] Although the data for the earthward ion flow region presented above shows a reversal in the field-aligned current structure, a similar analysis for the tailward flow interval (not shown) indicates persistent tailward electron flow for all distances from the NS. Hence no corresponding qualitative electron flow structure could be derived from these observations.

3. Discussion

[14] These burst mode observations in the plasma sheet during a clear reconnection event allow us to survey electron behaviour in order to clarify the physical processes driving reconnection. Data sampled by the Cluster spacecraft during the proton earthward flow period showed significant discrepancy in the parallel electron and ion flows. In the central plasma sheet the electron and ion flows were both directed earthward; In the outer part of the PS, however, electrons and ions moved in different directions producing an electric current directed away from the reconnection diffusion region. Such particle behaviour can be interpreted in terms of the collisionless reconnection model. In this model, the observed electron flows connect to the diffusion region closing the transverse Hall currents inside it. The existence of such current layers is confirmed by the simultaneous and consistent observations of parallel electron flows with a direction reversal and an increase of the $B_{\perp y}$ magnetic field component at the same place in the PSBL, as defined by B^* or N_e. Such coincidence shows that an electron-driven parallel electric current exists on the edge of the PS and its direction is consistent with predictions of the Hall reconnection model and with previous magnetotail reconnection layer observations by Geotail [e.g., *Nagai et al.*, 2003]. However, electric currents in the PSBL could also be part of a global magnetospheric current system, for instance, the region 1 current [*Ueno et al.*, 2002], which is not directly connected with the Hall effect in the reconnection diffusion region.

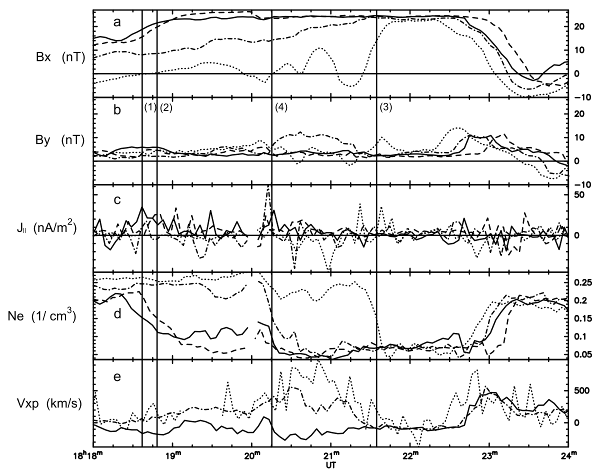

Figure 3. Cluster measurements during the proton earthward flow, as the SC exit the PS: FGM B_x and B_y components (a,b), the parallel electron current $J_{\|}$ (c), the electron density (d), CIS V_x proton velocity (e). Vertical lines corresponds to the $N_e = 0.15$ cm^{-3} for each spacecraft.

[15] In principle, Cluster data could be applied to determine the spatial scale of the current layers. Unfortunately, we are not able to use multi-spacecraft techniques for this case, but a simple estimation is still possible, assuming that observed magnetic field disturbance was produced by the observed parallel electron currents. Hence, to produce a $\sim$7 nT disturbance a current layer of $\sim$5 nA/m^2 currents should be $\sim$1000 km thick. This is consistent with previous estimations of *Fujimoto et al.* [2001]. Inside this current layer we observed a thinner layer of strong field-aligned currents with distinguished unidirectional beam-like phase space distributions. A possible explanation for such a reconnection layer feature comes from the fact that the density of heavy ions was relatively high during this interval. The positive electric charge density, contained in the heavier ion population was $\sim$30% of proton charge density, due to the high level of substorm activity [*Lennartson*, 1995]. Hence, our observations may be interpreted as two nested current systems from two nested diffusion regions: a bigger helium-oxygen diffusion region and a smaller proton diffusion region. In order to clarify the issue it will be necessary to determine the exact relation between the global reconnection parameters and the features of the electrons forming the current layer, which can be achieved by determining the exact electron acceleration mechanism. Also, study of the plasma waves could provide important information about the small scales plasma behaviour. Finally, global statistical surveys of various reconnection events are needed to estimate the relative importance of the various reconnection mechanisms.

4. Conclusions

[16] The electron flow structure in the PS during a reconnection event observed on September 13, 2002 was examined during a fast earthward ion flow period. The following facts were established:

[17] 1. The average parallel electron electric current changed direction at the edge of the PS: for the outer parts the current is directed away from the diffusion region, for the inner parts of the PS it is directed towards diffusion region. The thickness of the parallel current layer is $\sim$1000 km, which is comparable with the proton inertial length in the lobes.

[18] 2. Strongest outflowing electric currents (40–70 nA/m^2) were observed near the point of the averaged current sign change, at $B^* \approx 15$ nT ($\sim$60% of the north lobe magnetic field), $N_e \approx 0.15$ cm^{-3} ($\sim$60% of the NS electron density).

[19] 3. At the same point the largest transverse magnetic disturbances were detected.

[20] All these facts are consistent with the concept of collisionless reconnection in which a system of field-aligned currents flow in the PS and PSBL in order to close the Hall current in the diffusion region.

[21] No reconnection layer structure was resolved during the tailward flow due to the highly variable and turbulent conditions.

[22] **Acknowledgment.** This work was sponsored in the UK by the UCL/MSSL Particle Physics and Astronomy Research Council (PPARC) Rolling Grant. CJO acknowledges support via a PPARC Advanced Fellowship and JPD PPARC postgraduate studentship.

References

Balogh, A., et al. (2001), The Cluster magnetic field investigation: Overview of inflight performance and initial results, *Ann. Geophys.*, *19*, 1207.

Birn, J., et al. (2001), Geospace Environmental Modelling (GEM) Magnetic reconnection challenge, *J. Geophys. Res.*, *106*, 3715.

Fujimoto, M., et al. (2001), Tailward electrons at the lobe-plasma sheet interface detected upon dipolarizations, *J. Geophys. Res.*, *106*, 21,255.

Johnstone, A. D., et al. (1997), PEACE: A plasma electron and current experiment, *Space Sci. Rev.*, *79*, 351.

Lennartson, O. W. (1995), Statistical study of IMF B_z effects on energetic (0.1- to 16-keV) magnetospheric O^+ ions, *J. Geophys. Res.*, *100*, 23,621.

Lottermoser, R. F., and M. Scholer (1997), Undriven magnetic reconnection in magnetohydrodynamics and Hall magnetohydrodynamics, *J. Geophys. Res.*, *102*, 4875.

Nagai, T., I. Shinohara, M. Fujimoto, M. Hoshino, Y. Saito, S. Machida, and T. Mukai (2001), Geotail observations of the Hall current system: Evidence of magnetic reconnection in the magnetotail, *J. Geophys. Res.*, *106*, 25,929.

Nagai, T., I. Shinohara, M. Fujimoto, S. Machida, R. Nakamura, Y. Saito, and T. Mukai (2003), Structure of the Hall current system in the vicinity of the magnetic reconnection site, *J. Geophys. Res.*, *108*(A10), 1357, doi:10.1029/2003JA009900.

Rème, H., et al. (2001), First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment, *Ann. Geophys.*, *19*, 1303.

Runov, A., et al. (2003), Current sheet structure near magnetic X-line observed by Cluster, *Geophys. Res. Lett.*, *30*(11), 1579, doi:10.1029/2002GL016730.

Semenov, V. S., O. A. Drobysh, and M. F. Heyn (1998), Analysis of time-dependent reconnection in compressible plasmas, *J. Geophys. Res.*, *103*, 11,863.

Shay, M. A., et al. (2001), Alfvenic collisionless magnetic reconnection and the Hall term, *J. Geophys. Res.*, *106*, 3759.

Sonnerup, B. U. Ö. (1979), Magnetic field reconnection, in *Solar System Plasma Physics*, vol. 3, edited by L. T. Lanzerotti, C. F. Kennel, and E. N. Parker, pp. 45–108, North-Holland, New York.

Ueno, G., et al. (2002), Field-aligned currents in the outermost plasma sheet boundary layer with Geotail observation, *J. Geophys. Res.*, *107*(A11), 1399, doi:10.1029/2002JA009367.

I. V. Alexeev, J. P. Dewhurst, A. N. Fazakerley, and C. J. Owen, Mullard Space Science Laboratory, University College London, Holbury St. Mary, Dorking, Surrey RH5 6NT, UK. (ia@mssl.ucl.ac.uk)

A. Balogh, Imperial College, London SW7 2AZ, UK.

L. Kistler, University of New Hampshire, Durham, NH 03824, USA.

B. Klecker, Max-Planck-Institut für extraterrestrische Physik, D-85748 Garching, Germany.

H. Rème, Centre d'Etude Spatiale des Rayonnements, 9, avenue du Colonel Roche, Boite postale 4346, F-31028 Toulouse Cedex 4, France.

A. Runov, Institut für Weltraumenforshung der ÖAW, A-8042 Graz, Austria.